Design of an Extended Mission for GRAIL

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The GRAIL extended mission will extend the measurement of the lunar gravity field beyond what was achieved by the primary GRAIL mission this past spring (2012). By lowering the orbits of the two GRAIL spacecraft to less than half the altitude of the primary mission orbits on average, the resolution of the gravity field measurements will be improved by a factor of two, yielding a significant improvement in our knowledge of the structure of the upper crust of the Moon. The challenges of flying so low and the design which will meet those challenges is presented here.

Nomenclature

e eccentricity

Symbols

ΔV change in velocity, m/s

ω argument of periapse, degrees

I. Introduction

GRAIL,[1] the Gravity Recovery and Interior Laboratory mission, has successfully completed gathering data for the first global high resolution gravity map of the Moon, one that most notably improves the accuracy of the gravity model of the far side of the Moon by a factor of 1000. At the end of August 2012 (a week after this paper is presented), the two GRAIL spacecraft will begin to maneuver themselves into the science phase of an extended mission which will improve that gravity map by another factor of 2. This paper describes that extended mission.

GRAIL is a direct descendent of GRACE, the Gravity Recovery and Climate Experiment mission. Both missions placed two spacecraft in orbit, one behind the other, and derived their relative velocity from precision interspacecraft range measurements made from a Ka-band radio signal. Since the orbits were in a nearly polar orbit plane which was nearly fixed inertially, these measurements could be made over the entire Moon as it slowly rotated under the orbit.

I.A. The science of GRAIL

The science objectives of the GRAIL primary mission (PM) are to develop a high resolution lunar gravity field in an effort to understand the internal structure and thermal evolution of the Moon and to extend that knowledge to other terrestrial planets within the inner solar system. These objectives led to a series of different science investigations examining the Moon *"from crust to core"*. The resolution of the global, regional, and local scale gravity measurements of the upper mantle and crust during the primary mission were limited by the altitude of the primary mission's science orbit, which was an average of 55 km.

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The main science objectives in the extended mission involve investigations that require an understanding of density variations within the lunar crust and maria, both horizontally and with depth. Lowering the orbit altitude to approximately 23.5 km during the extended mission (XM) increases both the spatial resolution and accuracy of the gravity measurement as illustrated by figure 1, creating the opportunity to perform an entirely new set of ground-breaking science investigations focused on the upper crust. With a spatial resolution of under 15 km at the lower altitude, the sensitivity of the gravity measurement will now be at a scale that is a fraction of the average thickness of the lunar crust. The new measurements will have the ability to reveal the structure beneath a wide range of small-scale impact, volcanic, and tectonic features. In addition, near-surface features with no visible signature on the surface may also be detectable, including craters covered by lava during the flooding of impact basins, subsurface water-ice reservoirs in permanently shadowed craters near the poles, and even lava tubes. The gravity data acquired during the extended mission will also establish constraints to help address long-standing questions about the asymmetry of the crustal thickness of the near and far sides of the Moon, the formation of lunar rilles, and the origins of magnetic anomalies on the Moon.

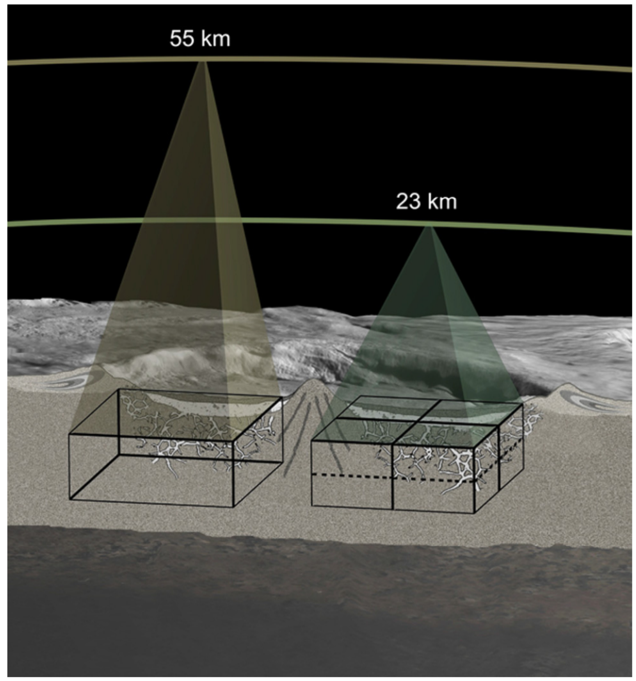

Figure 1. Schematic comparison of resolution in the primary (left) and extended (right) missions illustrates the ability in the XM to resolve near-surface structure not possible in the PM.

The data collected during the extended mission will be used to develop a new global gravity field, separate and distinct from the gravity field developed during the primary mission. While the XM field is sensitive to smaller scale features than the PM field, it nevertheless is also sensitive to features of the same scale observable in the PM data. As a result, additional insight can be obtained by investigating the differences between the PM and XM fields. In other words, differencing the two gravity fields may reveal information about small scale structures that are not clearly visible in either field alone. This is effectively equivalent to using the GRAIL mission as a gravity gradiometer at the Moon.

The GRAIL mission was selected as part of the NASA Discovery Program. As such, it is a science mission first and foremost. Nevertheless, the gravity fields developed from the PM and XM missions will greatly assist navigation for future human and robotic missions to the Moon, particularly those that require precision landing. In addition, ability of the GRAIL extended mission to identify and locate features such as lava tubes may be beneficial to future human exploration as a protective habitat for astronauts during solar storms.

I.B. The original mission design of GRAIL

The GRAIL spacecraft was based on an existing spacecraft design to provide design heritage and thus minimize mission cost. This spacecraft did not include any articulation for solar arrays (after deployment), telecom, or instruments. The antennas for the Ka-band transceivers were mounted on each spacecraft parallel to the solar arrays so that when the two spacecraft pointed their Ka-band instruments at each other, the spacecraft could fly with their solar arrays parallel to the orbit plane, as shown in figure 2 on the next page. This would make nearly constant power available during the non-eclipsed portion of each orbit. The system was designed so that this geometry would allow sufficient power for spacecraft and science needs as long as the Sun was at least 49 deg out of the orbit plane. This geometry repeats twice a year, approximately three months apart. The GRAIL orbiters can take advantage of each of these opportunities by simply controlling the order of the orbiters. The PM chose the March 8 to May 29, 2012 opportunity, which requires GRAIL-B to be in the lead position. Since the orbit plane is very nearly fixed in its inertial orientation, this would allow 82 days of gravity science at one stretch while the Earth-Moon system revolves around the Sun. By design this 82 day science campaign allowed three complete lunar revolutions under the orbit, giving three

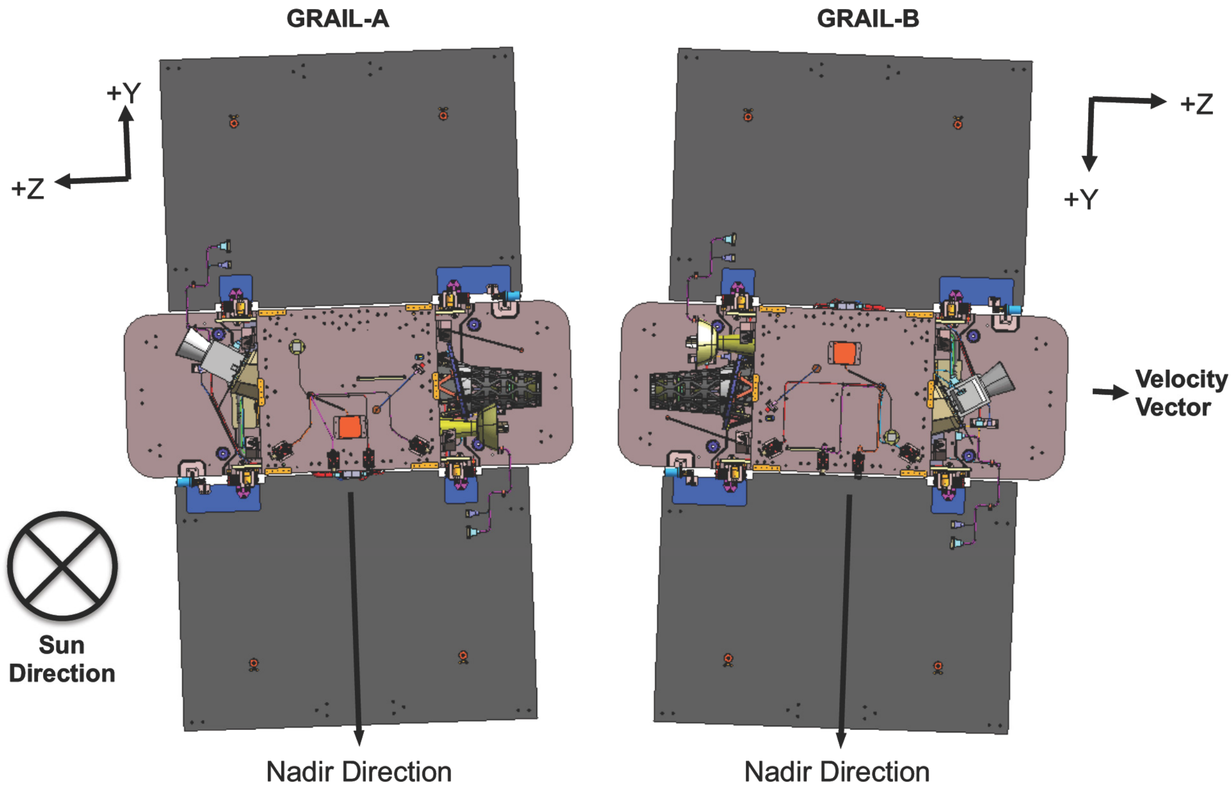

Figure 2. The two GRAIL spacecraft are nearly identical in their construction, differing only in the angles that the Ka-band antennas and the star trackers make with the spacecraft +Z axis. The solar arrays as shown are mounted on the far side of each spacecraft, facing the Sun. During the Science-XM Phase, the Sun will be on the far side of the plane of the arrays.

complete assessments of the gravity field on each of the ascending and descending sides of the orbit.

Because of the non-uniform nature of the gravity field at the Moon, the orbit is not stable in its position. The eccentricity vector of the orbit (which points toward the periapse and has magnitude equal to the eccentricity) moves in both length and in angle from the equator, but in general the altitude of the ascending node of the orbit decreases and the altitude of the descending node increases. The altitude of the science orbit for GRAIL was chosen to be as low as possible while starting with the ascending node high enough that no maneuvers would be needed during the primary science phase.

Phases of the mission are shown in figure 3 on the following page. These phases include the Launch Phase, the Trans-Lunar Cruise (TLC) Phase, the Lunar Orbit Insertion (LOI) Phase, the Orbit Period Reduction (OPR) Phase, the Transition to Science Formation (TSF) Phase, the Science Phase, and the Decommissioning Phase. The two GRAIL spacecraft were launched together by a Delta II 7920H launch vehicle into low-energy transfers[2] to the Moon, which culminated in propulsive insertions one day apart into eccentric 11.5-hour polar lunar orbits. Lunar orbit operations[3] began with two series of periapse maneuvers on each orbiter in the OPR Phase to bring the orbit period down to two hours. Then in the TSF Phase a short series of progressively smaller maneuvers on both spacecraft brought them into formation in the science orbit to begin the Science Phase.

I.C. An opportunity arises

Throughout the development of the GRAIL primary mission, the possibility of an extended mission was discounted for two reasons, both stemming from the GRAIL spacecraft heritage from an Earth orbiter design. The first reason had to do with the thermal design: an early analysis concluded that the spacecraft could not survive passage through any more than a very partial lunar eclipse while in the science orbit at the Moon because during a lunar eclipse the heaters would drain the batteries too much and the spacecraft would not be able to stay warm enough at critical points in the system. Thus the launch and transfer to the Moon were timed so that all lunar orbits (i.e. LOI through the Decommissioning Phases) occurred between lunar eclipses. The second reason had to do with the limited ΔV capability of the inherited propulsion system: one of the main drivers of the trajectory design for the primary mission was the need to keep the ΔV requirements of the mission within the capability and this was a recurring concern during mission development as the estimates of the mass of the spacecraft with its payload fluctuated while the design matured.

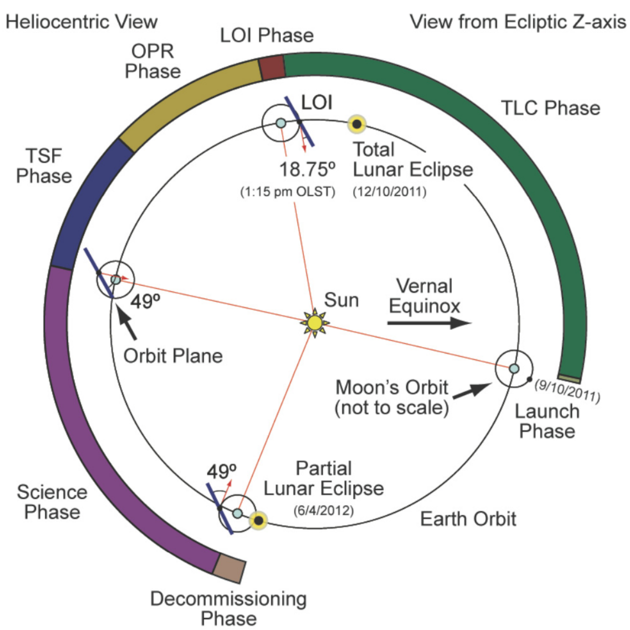

Figure 3. This view from ecliptic north relates the various phases of the primary GRAIL mission to the geometry of the orbits involved. The large circle is the Earth's orbit around the Sun (yellow disk in the center), the small circles show the Moon's orbit around the Earth (small blue disc on the large circle), and the short line segments centered on the Moon (small black dot on each small circle) show the orbit plane of the polar lunar orbits established by the LOI. Lunar eclipses are marked by a black dot on top of a yellow disk at the positions on Earth's orbit corresponding to the dates of the eclipses.

Shortly before GRAIL's launch on September 10, 2011, as the mass of the spacecraft and its payload became better determined and came out less than expected, we realized that with a favorable launch date and an accurate launch and maneuver executions there might be significant propellant left at the end of the mission. Since the propellant constraint on the extended mission might be removed, the question arose as to whether there was a way around the thermal constraint. An analysis was done to reassess the eclipse survivability issue. A more detailed analysis of the thermal and power subsystems found that without the conservative simplifying assumptions of the initial analysis from years earlier, and with the final as-built design of the hardware in hand, the spacecraft would indeed survive the passage through Earth's shadow. At first it seemed that it might be necessary to carefully phase the spacecraft positions in lunar orbit with respect to the time of the Moon's entry into Earth's shadow, but in fact it was found with further analysis and simulations that the spacecraft systems are robust enough that survival was assured independent of that phasing.

As the primary mission progressed, the amount of fuel available for an extended mission became more definite. An early and energetically favorable launch date, a near-perfect launch injection, 28 maneuvers executed within expected performance, and an absence of unplanned contingency recovery maneuvers were all factors that resulted in having enough propellant at the end of the primary mission to take advantage of the second favorable Sun-Moon geometry in the Fall of 2012. With sufficient ΔV available, the prospect of a healthy spacecraft after the lunar eclipse, and the successful completion of the primary GRAIL mission, the mission design goal then became to achieve the lowest orbit at the Moon, with the least variation in altitude, that was feasible when considering the cost and risk of flying it.

II. Design of the GRAIL extended mission

The mission design of the extended mission starts with the goal of repeating the gravity measurement campaign but in an orbit that is as low as can reasonably be achieved. Because of the spacecraft configurations, as explained above in section I.B on page 2, this gravity campaign could next be done between August 30 and December 10 of 2012, when the Sun would once again be at least 40 degrees from the orbit plane of the GRAIL spacecraft. Note that this bounding value for the Sun's angle from the orbit plane is less restrictive than the angle of 49 degrees used in the primary mission. The 49 degree beta angle limit was set as a design requirement for spacecraft capability in order to allow enough time for three complete mapping cycles in the primary Science Phase. As with the eclipse analysis, analysis of the spacecraft as built showed that it had more capability than was required. In fact, the spacecraft power system can support loads in orbiter-point down to solar beta angles as low as 40 degrees, so continuous gravity measurement can begin as early as August 30.

The various phases of the extended mission are shown in figure 4 on the following page. They start with the Lunar Eclipse (LEC) Phase (which replaced the Decommissioning Phase of the original mission), followed by the Low Beta-Angle (LBA) Phase, the Transition to Science Formation-Extended Mission (TSF-XM) Phase, the Science-XM Phase, and finally a new Decommissioning Phase, which may extend a few days or weeks beyond the time indicated in the figure depending on whether the mission takes advantage of any final science opportunities.

II.A. How to survive until the science phase

As discussed in section I.B on page 2, the altitude of the ascending node of the GRAIL orbit tends to decrease with time; the periapse is not always at the ascending node but does move toward low latitudes on the ascending side of the orbit after the orbit has evolved sufficiently. In the design of the primary mission, this would have resulted in the spacecraft crashing into the surface shortly after the partial lunar eclipse on June 4. So even though the spacecraft could have survived the eclipse, a maneuver was needed to keep the spacecraft flying.

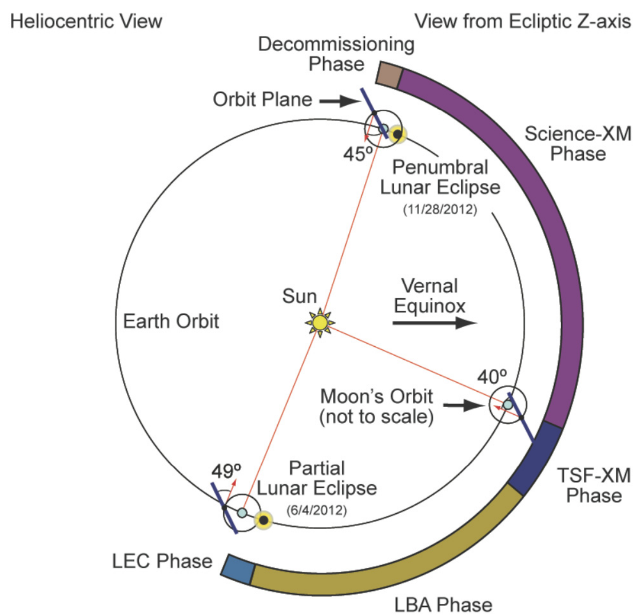

Figure 4. This view from ecliptic north relates the various phases of the extended GRAIL mission in the same view and imagery as in figure 3 on the preceding page.

A pair of Orbit Circularization Maneuvers (OCMs) were designed, one for each spacecraft, to accomplish six goals: 1) reorient the orbit to avoid the impending impact with the lunar surface, 2) set up the spacecraft for a three month quiescent period (LBA Phase) to wait for the required Science-XM Phase Sun-Moon geometry, 3) minimize the ΔV needed to get to the science orbit to begin the Science-XM Phase while meeting the other goals, 4) target the eccentricity vector to a position so that after three months of orbit evolution a single Eccentricity Correction Maneuver (ECM) could establish the science orbit, 5) control the relative position of the two spacecraft to put GRAIL-A in front of GRAIL-B, and 6) achieve a separation distance of at least 665 km on August 20, 2012 at 15:00 UTC.

While there are a multitude of orbits that could easily accomplish the first two goals, the third and fourth goals dictated that the OCMs target to an 85 km near-circular orbit. As will be discussed in the following section, the requirements of the science phase dictated a particular semi-major axis and eccentricity vector for the orbit at the start. This meant that the total motion in eccentricity space provided by the maneuvers at either end of the LBA Phase had to compensate for the evolution of the eccentricity vectors during the phase while moving the eccentricity vector to the specified location at the end.

Since the general motion of the orbit evolution is left to right in e-ω space, we needed the beginning and ending maneuvers on each spacecraft to provide a large shift of the eccentricity vector to the left, and it was already known[4] that this could most efficiently be done with maneuvers in the same $\omega = 270$ deg direction and tangential to the orbit. These two maneuvers, the OCM and the ECM, also had to combine to reduce the semi-major axis from the 55 km of the primary Science Phase to the value needed for the Science-XM Phase. As a result, the OCM needed to be a tangential orbit raise maneuver somewhere around the descending node, the ECM had to be a tangential orbit lowering maneuver on the opposite, ascending, side of the orbit, the sum of their magnitudes provided the proper amount of eccentricity vector shift, the difference of their magnitudes provided the desired change in the semi-major axis, and their in-orbit locations were determined by the direction of the total eccentricity vector shift. To first order these constraints on the OCM and ECM define them in position, magnitude, and direction. (As will be seen in section II.C.4 on page 14, further consideration led to a modification in the ECM that ends the LBA Phase, but this did not affect the OCM design.) The effectiveness of the OCM and ECM combination in controlling the altitude of GRAIL-B is shown in figure 5 on the next page; the altitude of GRAIL-A follows the same profile with a one-orbit shift in maneuver timing.

The OCM, then, moves the orbit up-and-to-the-left in the eccentricity vector space, allowing for the

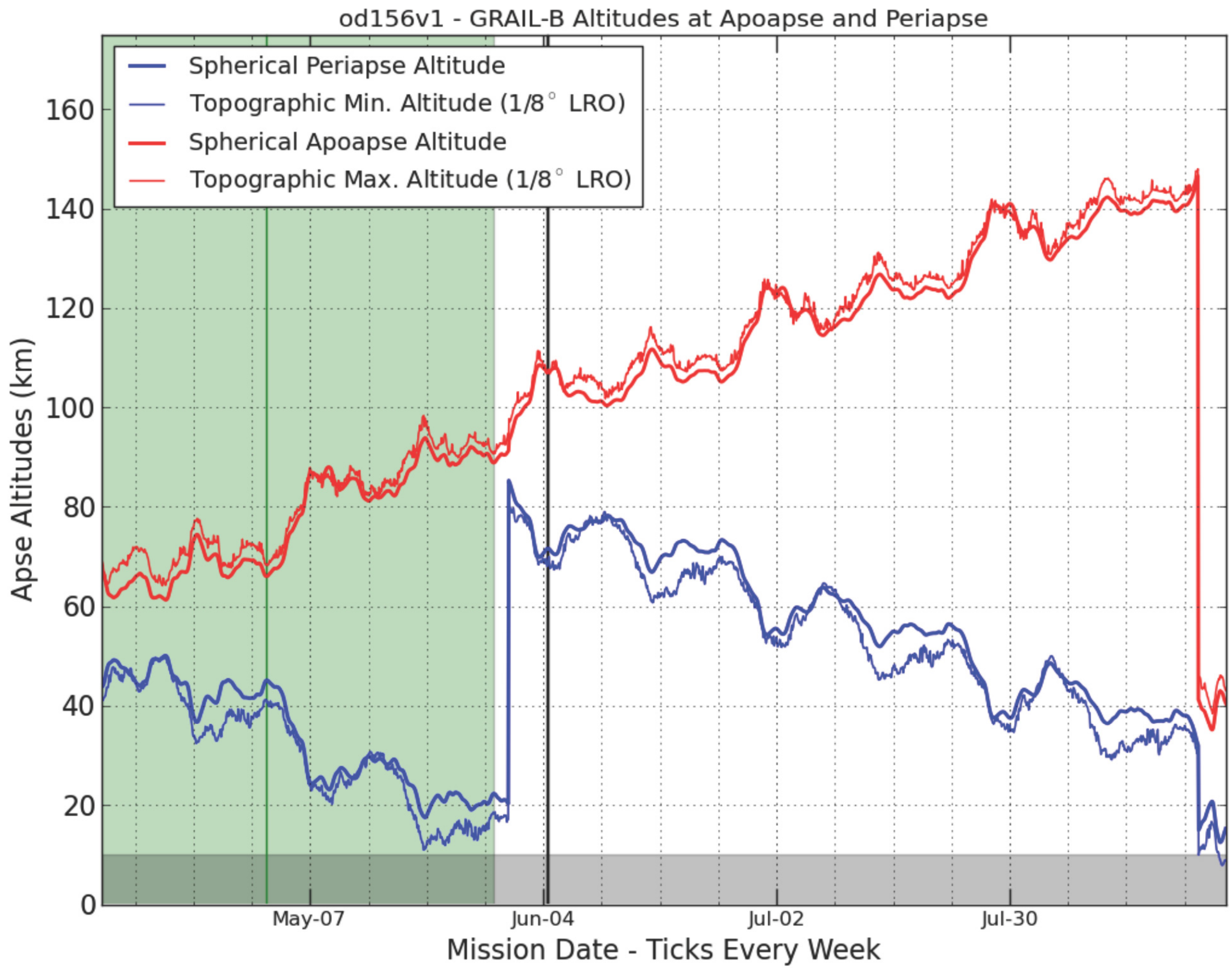

Figure 5. A plot of the altitude of GRAIL-B during the LBA Phase for a design wherein the combination of OCM and ECM put the orbit in the science orbit directly. Later, as discussed in section II.B on the next page, modification of the ECM-1 design would leave the spacecraft at a higher altitude after the ECM is executed.

general down-and-to-the-right evolution without requiring any large maneuvers during the LBA Phase. The periapse and apoapse altitudes shown in figure 5 are near each other at approximately 85 km and start to diverge reaching 34.5 km and 142 km, respectively, at the time of the first Eccentricity Correction Maneuver (ECM) in the TSF-XM Phase on August 20, 2012.

Power and Thermal analyses showed that both of the orbiters would be able to survive the June 4 partial lunar eclipse in any relative orbit geometry, i.e., the orbiters could be at any true anomaly when the eclipse started. This allowed for flexibility in the timing of the OCMs. A date of May 30, 2012 was chosen to allow for the opportunity to execute a backup OCM before the eclipse in the event of a contingency situation, while the times of the maneuvers were chosen for observational and operational convenience.

OCM-B1 (for GRAIL-B) and OCM-A1 (for GRAIL-A) were performed one orbit apart on May 30, 2012. Having GRAIL-B go into the larger orbit first allowed for GRAIL-A to speed ahead of GRAIL-B during the two hours between maneuvers, placing GRAIL-A in the lead position as required by the Science-XM Phase. OCM-A1 targeted a slightly different period than OCM-B1 to impart a slow drift apart to achieve the 665 km separation in August. The planned separation distance profile assuming no OCM execution errors during the LBA Phase is shown in figure 6 on the next page. An Orbit Trim Maneuver (OTM) was included in the LBA Phase schedule to adjust the separation distance between the two orbiters. On June 20, 2012, this maneuver, OTM-B3, was performed mainly to clean up the OCM execution errors. The effect on the separation distance profile can be seen clearly in figure 6. The navigation team was prepared to add an OTM-B4 in August to correct for any orbit determination (OD) or execution error in the performance of OTM-B3, but it turned out not to be needed.

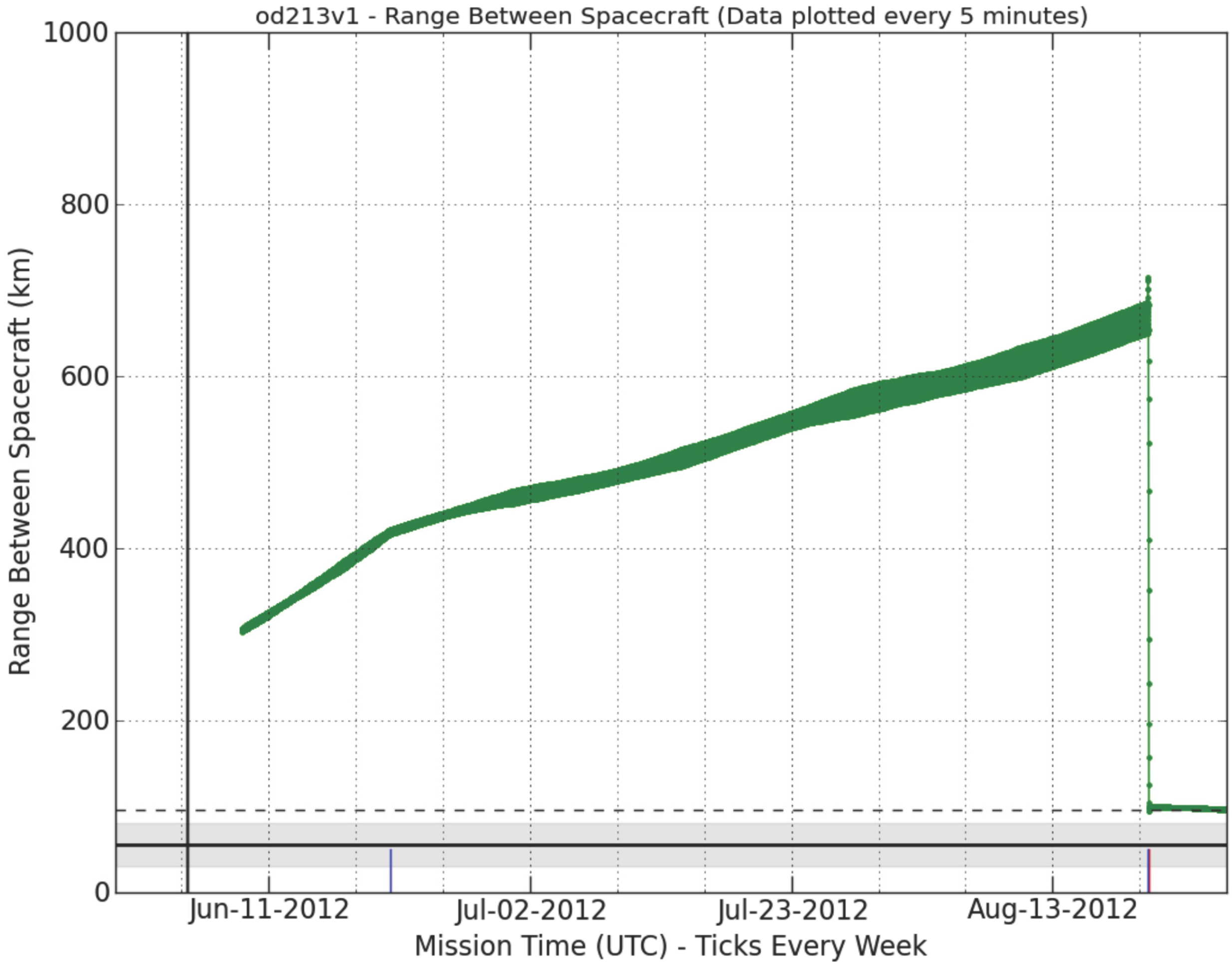

Figure 6. A plot of the separation between GRAIL-A and GRAIL-B during the LBA Phase and the beginning of the TSM-XM Phase.

II.B. Transitioning to the Science Phase

Controlling the separation distance after the OCMs significantly simplified the TSF-XM Phase in comparison to the complex TSF Phase in the primary mission.[3] As discussed in the previous section, for each orbiter the OCM was designed so that a single tangential ECM could reduce the period and target the eccentricity vector to the left side of the eccentricity vector space, flipping the line of apsides and turning the pre-maneuver periapse altitude into the post-maneuver apoapse altitude, so that each orbiter would be in orbit at the start of the orbit pattern designed for doing science. The design of that orbit pattern is described in the following section and includes weekly ECMs on Mondays to keep the orbit altitude as low as could feasibly be managed. We decided to begin the weekly maneuvers at least a week before the beginning of the Science-XM Phase on August 30 (see section II on page 4) to make sure that the orbiters would be in formation and ready to make gravity measurements from the very start of science.

Maneuver durations on the GRAIL spacecraft are controlled by accelerometers on board so that the maneuver magnitudes can meet the stringent accuracy requirements of the GRAIL mission. But for safety, in case there is some problem with the acceleration estimate in the control system, there are overriding timers which prevent a burn from being too much shorter or longer than expected. For the ECMs this timer system is set to allow a 6% variance, the minimum value that the spacecraft team judges would give a high probability that functioning control system would stop the maneuver at the desired magnitude. This caused some concern in the case of ECM-1, since a 6% overburn of the originally planned ECM-1 would put the periapse of the orbit below the surface of the Moon. To guard against this possibility, the targeted period change of ECM-1 was reduced by 6% and the eccentricity target for it was adjusted accordingly. Then a tangential component was added to ECM-2 to finish the period reduction needed to bring the orbit size down to the average altitude planned for science, while still targeting the same eccentricity vector position as before.

During the formulation of the extended mission, we planned to have every pair of OCMs and ECMs be performed on successive orbits so that the operations team could concentrate on one maneuver at a time. We chose to have GRAIL-B maneuver first because with the OCMs this allowed GRAIL-B to leapfrog back over GRAIL-A and get into a trailing position as mentioned in the preceding section. Then, by doing ECM-B1 one orbit before ECM-A1, GRAIL-B would drop into a lower, faster orbit and approach GRAIL-A, removing most of the separation between them. This would again happen between ECM-B2 and ECM-A2, but the approach would be much slower because the period change from ECM-2 is much smaller. The sizes of these separation drops is determined by the period changes designed into ECM-1 and ECM-2, so the final separation distance is controlled largely by the separation rate before ECM-1, which was set by OTM-B3 as discussed above in section II.A on page 5.

II.C. The design process for the science phase

II.C.1. Initial trade studies to determine the trajectory architecture

While the Moon is more spherical than the Earth, its gravity field is still irregular enough to push spacecraft orbits around, both in the short term and secularly. In a low, near-circular, near-polar lunar orbit like GRAIL's, the semi-major axis, inclination, and longitude of ascending node all oscillate somewhat with a bi-weekly period, and the longitude of the ascending node also precesses slowly, but the real action is in the eccentricity and argument of periapse. So to understand the evolution of a lunar orbit the best picture of it is the path of its eccentricity vector. Since both spacecraft would be in the same orbit to enable the science measurements, the discussion in this subsection refers to the design of that orbit.

Since the goal of the extended mission is to make measurements to allow generating a global gravity map with resolution as much higher than the primary mission's as could be achieved, the goal for the trajectory design was to minimize both the average altitude of the spacecraft and the variation in altitude of the spacecraft, within bounds of flight risk and operational costs. This meant using maneuvers to shift the position of the eccentricity vector in eccentricity vector space (whose polar coordinates are eccentricity and argument of periapse), making use of methods previously reported by Sweetser.[4] (The application of these methods, and other processes involving the orbit evolution, are only summarized here; they are detailed elsewhere by Wallace, Sweetser, and Roncoli.[5]) After the orbit has been repositioned, the evolution of its eccentricity vector continues to move in almost exactly the same pattern as it would have followed if not shifted, so it is possible to keep recentering the pattern of orbital evolution.

One of the factors which determines the measurement resolution, besides the altitude of the spacecraft, is the maximum spacing between ground tracks. Since we wanted to minimize the number of maneuvers in general, this precluded any complicated pattern of shifting ground tracks by changing the period. Instead, part of the design goal became keeping the ground tracks equally spaced by picking an appropriate average period and maintaining it, i.e., keeping the average altitude constant. The ground track spacing after one mapping cycle shifts by a third of a degree for every change of 1 km in orbit altitude; then within a kilometer of any otherwise desired altitude there is an orbit altitude we could select so that the ground tracks from the three mapping cycles would be interlaced and spaced about a third of a degree apart from each other.

Given a fixed average altitude the maximum eccentricity determines the maximum variation in altitude relative to a spherical Moon. This maximum depends on how the eccentricity vector moves across eccentricity vector space as the orbit evolves between maneuvers, since the maneuver at the beginning of each pattern segment of the evolution will be designed to center that segment. For any given number of maneuvers and segments, the timing of the maneuvers can be optimized to minimize the maximum diameter of the centered segments; once this has been done, the only way to reduce the maximum altitude variation is to increase the number of maneuvers.

Because of the shape of the pattern that the eccentricity vector makes as the orbit evolves, significant reductions in the variation occur when there are one, three, and seven maneuvers per mapping cycle. These contrast with the primary mission, which went through three mapping cycles without any maneuvers to shift the course of the eccentricity vector. The altitude variations observed for optimized cases with one, three, and seven maneuvers per mapping cycle were about 37 km, 30 km, and 23 km respectively. Further consideration by the project team, in consultation with the science team for GRAIL, led to focusing on the

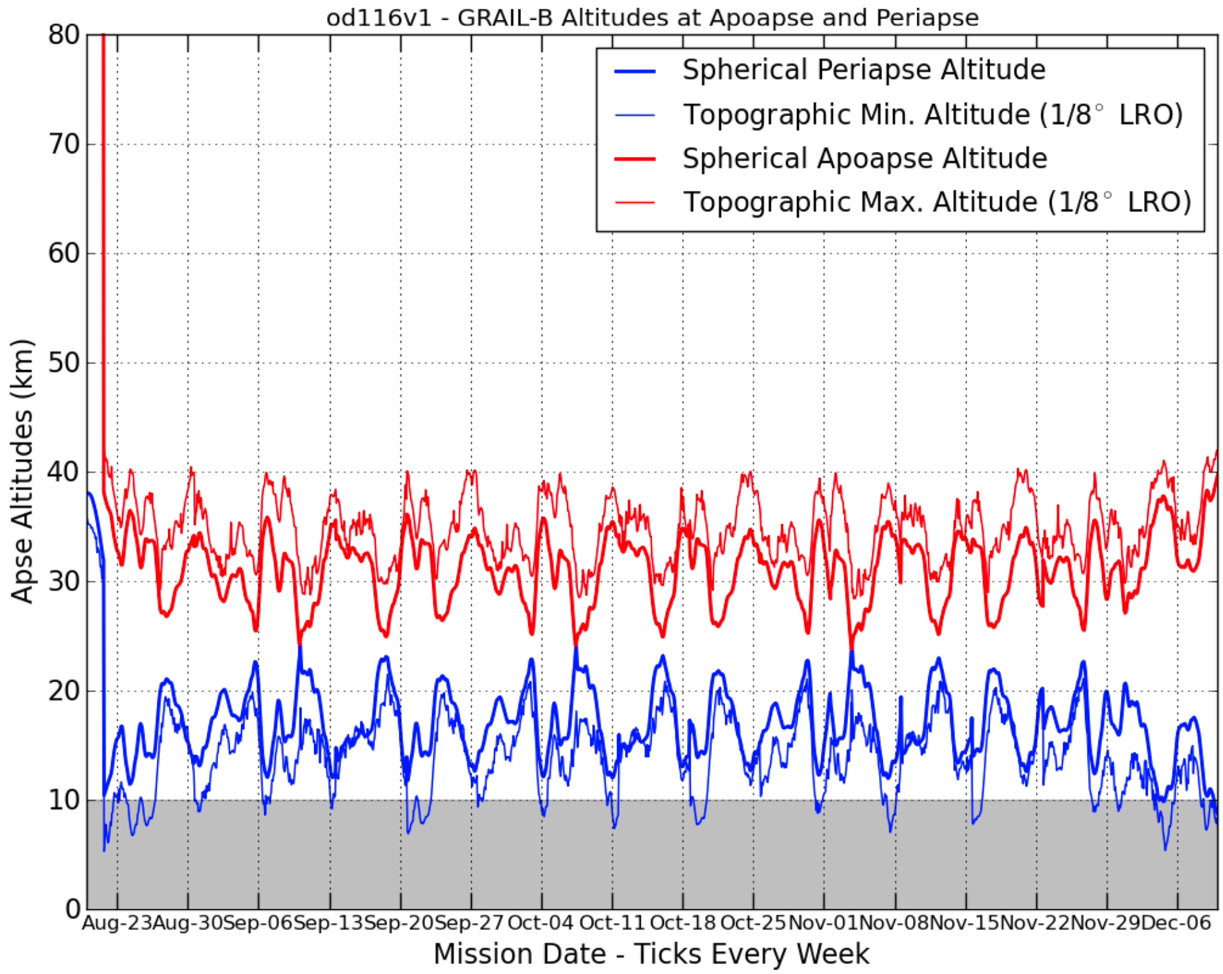

Figure 7. A plot of the topographical and spherical altitudes for a lunar orbiter which performs recentering maneuvers on Thursday mornings Pacific time with all the ECMs one orbit apart during the extended mission Science Phase.

three-maneuver option. This was seen to be the lowest variation option feasible, because jumping to seven maneuvers per four-week mapping cycle, with maneuvers occurring less than two days apart in some cases, would require increasing the size and cost of the extended mission operations team significantly over the size and cost of operations during the primary mission.

At this point in the development of the mission design, operational considerations led to a further refinement on the maneuver strategy. With three maneuvers per mapping cycle which were unevenly spaced (since their timing was optimized to minimize the maximum altitude variation), scheduling the operations processes (OD, maneuver design, sequence generation, and verifications and approvals for these) through the extended mission promised to be a major effort; more importantly, having a schedule which shifted from week to week was seen as an operations risk—there was too much opportunity for confusion. Instead, we suggested and the project agreed it would be easier operationally to increase the number of maneuvers to four per mapping cycle and space them exactly one week apart, allowing a repetitive schedule to be adopted. And as an advantage for development, having regular maneuvers allowed the development of an automated geometric algorithm[5] for optimizing them to minimize the altitude variation. When this was used to find a trajectory for the Science Phase with maneuvers on Thursday mornings (Pacific time), the topographical altitude variation was about 32 km and the spherical altitude variation was about 23 km or 24 km, as shown in figure 7.

At about this point in the mission development, additional considerations arose. A major one was, how low could we go? We didn't have any formal requirement in hand to decide this question. For the extended mission the project carried over the requirements from the primary mission, but left it to our judgement as mission designers to modify or disestablish them when changes in mission circumstances between the primary and extended missions had rendered them inapplicable. One mission requirement in the primary mission was that the spacecraft would never have a topographic altitude below 10 km during the Science Phase, which was found during development of the primary mission to be met when the spherical altitude was kept above 12 km. Several related circumstances, however, had changed for the extended mission: we now had a higher resolution and more accurate global topographic map in hand from the science results of the Lunar Reconnaissance Orbiter Mission; we had experience flying low lunar orbits and executing maneuvers in them; and, the main scientific goal now required the spacecraft to fly as low as reasonable. For the extended mission, the 10 km topographic altitude requirement was considered to be too conservative.

Another major new consideration, which also concerned altitude limits, was, what happens if a planned maneuver fails to execute? We didn't want to be in an orbit so low that a missed maneuver would not leave sufficient time to react before the spacecraft crashed; given the weekly operations planning, seven days seemed to be a reasonable requirement for lifetime in that situation. In other words, if a maneuver was missed the orbit should be designed so that the spacecraft would not crash before the next scheduled maneuver. All the maneuvers in the Thursday-maneuver design were checked against this internally imposed lifetime requirement and found to meet the requirement if the topographical altitude stayed above 8 km during the following week; moreover, they also met a proposed secondary requirement that if a maneuver is missed the altitude stay above a line that starts at 8 km and ends at 0 km over the second week after the last executed maneuver (i.e., during the week after the missed maneuver).

The operations team preferred that the weekly maneuvers be on Mondays, early in the morning local time (midafternoon UTC). This would allow OD and all the maneuver preparations for the next week's maneuver to be completed by the end of day on Thursday, leaving Friday and the weekend free as margin in case some difficulty is encountered during the week. To be thorough, for every day of the week we designed trajectories at an average altitude of 23.5 km maintained by weekly maneuvers and checked those trajectories against the lifetime requirements we had adopted internally. The Monday-maneuvers trajectory had slightly less altitude variation than the Thursday-maneuvers trajectory, so it met the altitude constraints with a couple of kilometers of margin, and it required no more than 10 m/s of ΔV more to fly, so it was adopted for operational reasons.

II.C.2. Defining and optimizing the science orbits

Having determined that a weekly maneuver on Monday was the appropriate approach, given the maneuver template timeline and the Project's desired risk posture, it became necessary to determine the specific semi-major axis, eccentricity, and argument of periapsis targets for each ECM. There were four driving requirements on the design: the mean altitude had to be such that the ground-track over the three mapping cycles was approximately uniform, the topographic altitude had to remain above 8 km between maneuvers, the topographic altitude had to remain above a time-varying value in the event of a missed maneuver, and the variation in the altitude was to be as low as feasible. This last requirement was qualitative, and so offered a lot of flexibility.

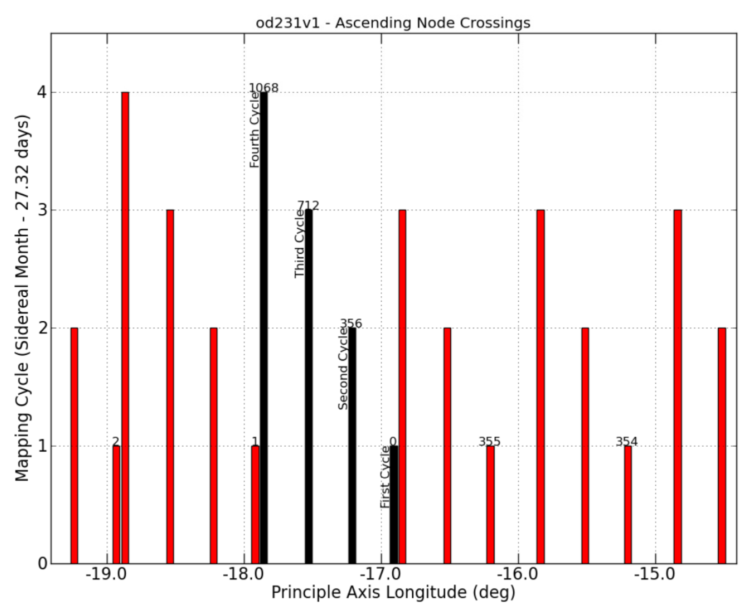

Figure 8. Bars here mark the longitude of the ascending node in Moon-fixed coordinates for some of the orbits during the Science-XM Phase. The height of each bar indicates which mapping cycle that orbit is in.

It was known from the early design work that an altitude of approximately 23.5 km would be achievable with weekly maneuvers, and that a total apoapse-to-periapse variability in the spherical altitude of 23 km was deemed satisfactory. The altitude was iterated upon during the design process until the ground-track, including the slow nodal precession, achieved a nearly three-month (82-day) repeat cycle. We chose not to target an exact 82-day repeat cycle, however, as the Science team preferred that the last two weeks of the Science-XM Phase not go over the exact same topography as the first two weeks. The ground-track plot, figure 8 on the previous page, illustrates the spacing of the longitudes of the ascending nodes at the start of each 27.3 day mapping cycle. As can be seen, the start of the fourth mapping cycle (starting with orbit 1068) is very near the start of the first mapping cycle, but not exactly on top of it.

The 23 km altitude variability was carried as a requirement, though one that could be violated if other, firmer requirements necessitated such action. The eccentricity vector evolution between Monday maneuvers was slightly more compact than the 23 km altitude requires; a variability of 19 km could be achieved by "centering" the least compact segment on an eccentricity-argument of periapsis at periapsis (e-ω) polar plot. So, using the method described by Wallace, Sweetser, and Roncoli (ref), a preliminary set of e-ω targets for each of the 13 ECMs after ECM-1 was determined by minimizing the discontinuities in e-ω space, subject to the constraint that the segments be within an e-ω circle equivalent to the 19 km variability but shifted to the "left" in e-ω space such that the maximum variability would be 23 km if the argument of periapsis was 180 deg. This constraint is the green circle in figure 9 on the following page.

However, though the minimum spherical periapsis altitude of this design would be 12 km, some of the optimized e-ω targets resulted in short-term violations of the 8 km topographic altitude requirement. In addition, the optimization did not include any consideration of an internally imposed requirement that the spacecraft survive sufficiently long to recover from a missed maneuver. By examining a plot like figure 10 on page 13, it was possible to manually adjust the e-ω targets for a given ECM by shifting them up-and-down, left-and-right, or some combination. It was useful to consider the e-ω target in a Cartesian projection such that the abscissa was a*e*$cos(\omega)$ and the ordinate was a*e*$sin(\omega)$. That way, a 4 km violation in the topographic altitude requirement, such as that highlighted by the dashed circle in the top half of figure 10 on page 13, could be corrected by shifting the segment left by 2 km to remove the violation. It was a straightforward process to translate such a shift back into eccentricity and argument of periapsis targets. This adjustment comes as some cost the total mission ΔV, as the original target was ΔV-optimal, but this was a small price to pay to satisfy other requirements. Of the 13 ECM targets designed using this process, most had to be manually adjusted in this way. Fortunately, they all generally moved in the same direction and the net cost was only 8 m/s increase in the total mission budget.

II.C.3. Not just one spacecraft, but two in formation

During the GRAIL primary mission, the modus operandi was for GRAIL-A to essentially ignore GRAIL-B and setup the initial conditions to start the Science Phase. GRAIL-B's job was to fly in the same orbit as GRAIL-A. In the GRAIL extended mission, this philosophy has reversed. The maneuvers performed on GRAIL-B now control the period to get the desired ground-track spacing and the eccentricity vector targets are chosen to maintain the minimum topographic altitude, minimum lifetime, and altitude variation requirements. It is up to GRAIL-A to now maintain the separation distance profile, which includes keeping close to GRAIL-B in the eccentricity vector space.

Due to the invariant pattern of the eccentricity vector evolution around the Moon, the eccentricity vector targets for both orbiters can be chosen and fixed prior to executing a single maneuver. Even with the inevitable maneuver execution errors, these targets can remain fixed. Therefore the maneuver design process is rather straightforward; using an inertially-fixed burn, optimize the timing, direction, and duration of the burn to achieve the given eccentricity and argument of periapsis while correcting for any period differences caused by previous maneuver execution errors. In the case of GRAIL-B, this latter means correcting back to the nominal period; in the case of GRAIL-A this means targeting to the desired 55 km separation between the orbiters at the time of the next ECM.

In the absence of such period errors the direction of each ECM maneuver during the Science-XM Phase would be perpendicular to the velocity vector to keep the period unchanged, thus making these maneuvers almost entirely radial. ECM-1 and ECM-2, which occur before the Science-XM Phase begins, are special cases that were discussed in section II.B on page 7, but also have targets that are known in advance. The direction of every ECM is further constrained to be in-plane to maintain the nearly-polar orbit. Because these targets are fixed, the entire reference orbit for GRAIL-B can be designed independently from GRAIL-A and can be completed through the last ECM, which is ECM-14 on November 19, 2012. Then the reference orbit for GRAIL-A can be designed to maintain the desired separation from GRAIL-B, as shown in figure 11 on page 14.

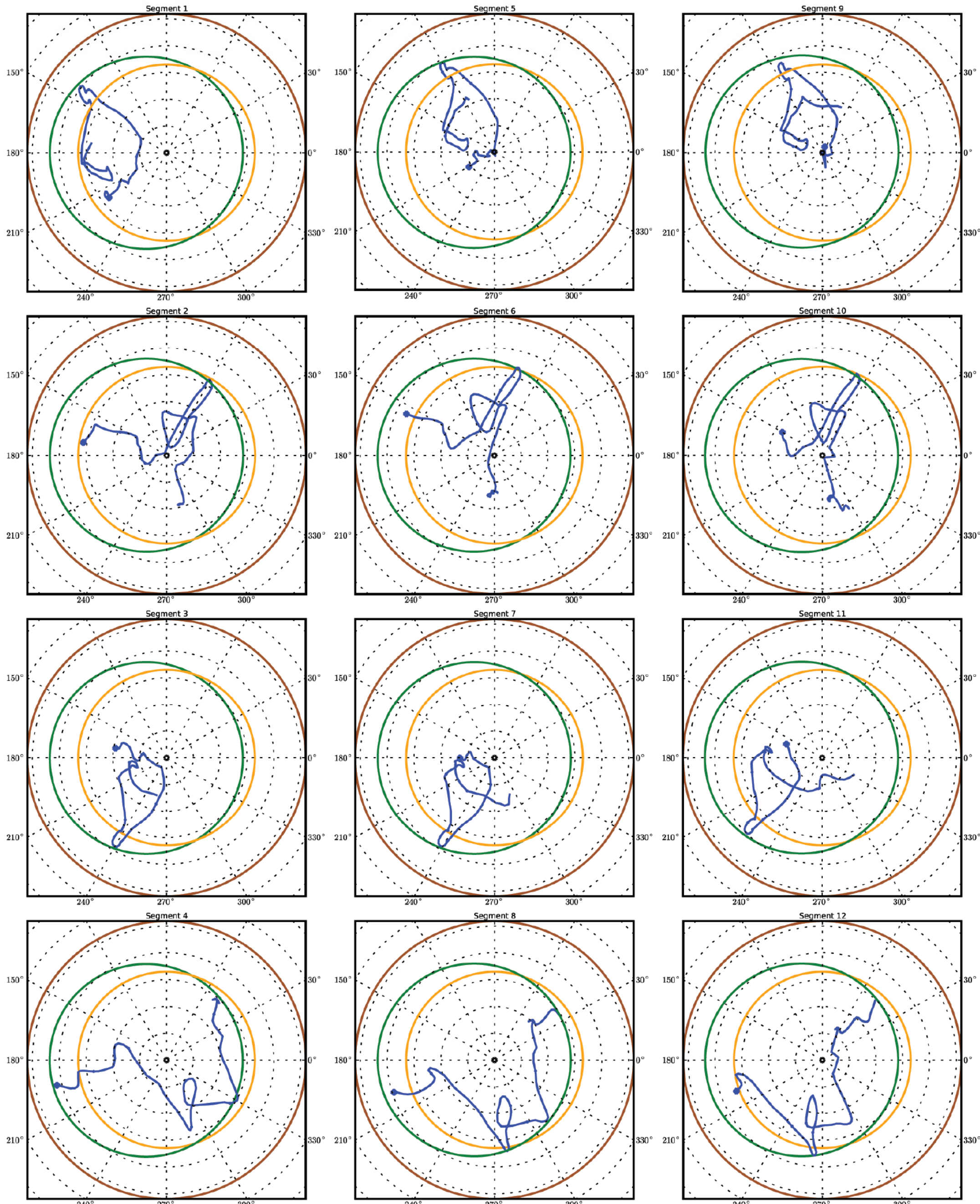

Figure 9. The orbit evolution during the Science-XM Phase is broken into week-long segments, which are shown as paths of the eccentricity vector in $e - \omega$ space, and the position of each segment has been selected to minimize the ΔV required to accomplish the mission.

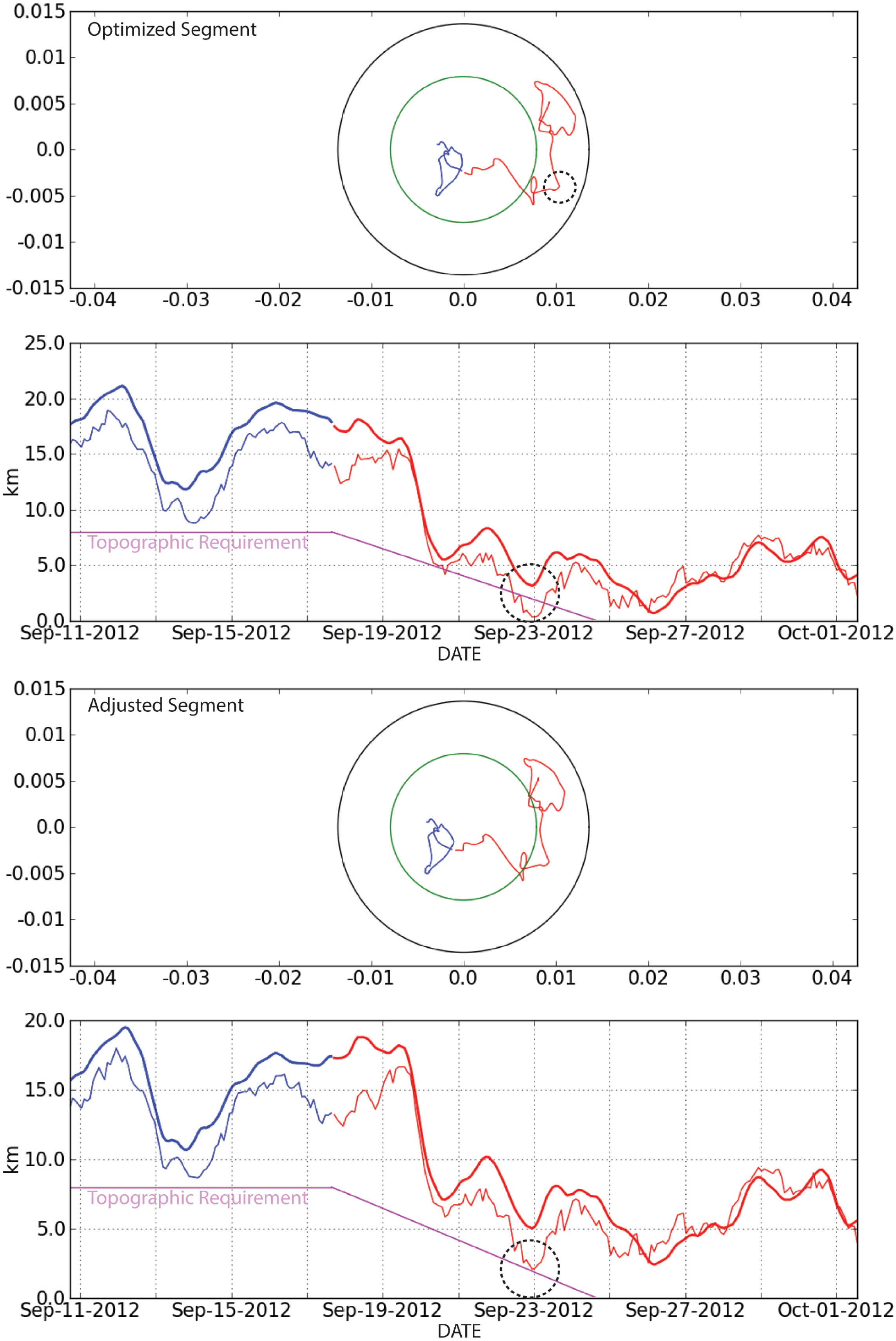

Figure 10. Positions of an orbit evolution segment and their resulting altitudes before and after a position adjustment is made to ensure adequate altitude is maintained long enough for recovery after a missed maneuver. This segment starts with ECM-4 and shows the orbit evolution if ECM-5 is missed.

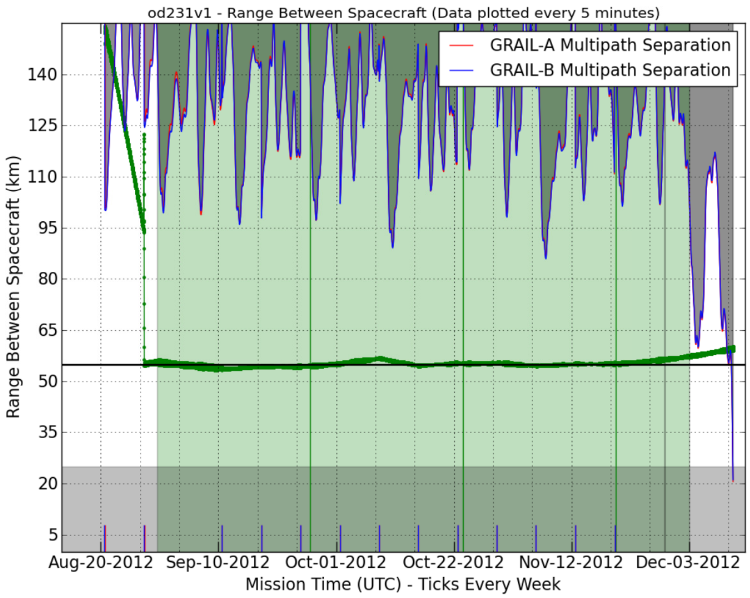

Figure 11. This plot shows the separation between GRAIL-A and GRAIL-B in their reference trajectories during the Science-XM Phase, starting before ECM-2. The green shaded area is the Science-XM Phase; the grey shaded areas are separations where the gravity measurement is degraded because either the Ka-band antennas are too close to each other or the spacecraft are far enough apart that there is multipath interference from the surface of the Moon.

For each ECM pair in the Science-XM Phase (i.e., starting with ECM-4), the project has chosen to execute the ECMs on the same orbit in order to avoid large excursions in the separation that would occur if the ECMs were on different orbits. These excursions would happen because the orbiters would be on different orbits between the ECMs and the order of the periapses and apoapses would differ, causing the orbiters to speed up and slow down relative to each other. On the reference trajectories doing the maneuvers on the same orbit means that the GRAIL-A maneuvers and GRAIL-B maneuvers are effectively the same, performing the same change in the eccentricity vectors and keeping the period unchanged, and happen at the same point in the orbit. But because GRAIL-A is 30 seconds ahead of GRAIL-B in the orbit, it begins each ECM in the Science-XM Phase 30 seconds before GRAIL-B.

In actual flight, when every maneuver does have execution errors, each ECM will be designed to contain a small tangential component to correct period errors as discussed above. In order to keep the change in the eccentricity vector the same when the tangential component is included, it can be shown using techniques described in Sweetser[4] that the position of the maneuver on the orbit will have to change by as much as a degree (3σ), which corresponds to about a 20 s change in the timing of the maneuver. This is probably (3σ) not enough to change the order of the start times of the maneuvers.

The GRAIL-B maneuvers can be performed at two different locations, or true anomalies, on any given orbit to achieve the period, eccentricity, and argument of periapsis targets. At one true anomaly the ΔV direction is radially outward from the Moon, while at the other location is radially inward toward the Moon. As far as GRAIL-B is concerned, the maneuver can happen at either true anomaly but the radially outward maneuvers always happen on the reference trajectories within view from Earth, allowing us to track the orbiters through the maneuvers. Given the choice of the radially outward maneuver, the separation distance initially increases in the event of a missed ECM-A maneuver and decreases in the event of a missed ECM-B maneuver, since the orbiter that performs the maneuver will go into an initially higher orbital path that slows it down. The maneuvers were chosen to happen at the first visible true anomaly after 08:00 local Pacific Time (15:00 UTC during Standard Time, or 16:00 UTC during Daylight Savings Time).

II.C.4. Designing for execution errors and contingencies

With a complete trajectory architecture in hand, the next level of design was to refine the design to make it robust in the presence of errors and mishaps—we started asking ourselves "What if?" and, in the case of maneuver execution errors, "How much?" Actually, the need to provide for ECM execution errors was recognized from the beginning, and an orbit trim maneuver (OTM) was planned for one day after each ECM pair. Because the ECMs (after the first one) are primarily radial maneuvers, any magnitude error has the effect of an error in the eccentricity vector achieved since the error affects the resulting flight path angle; an analysis of the expected variation in the eccentricity vector showed that it was well within mission requirements and in any case it would be corrected in the targeting of the next ECM maneuver pair.

On the other hand, pointing errors in the ECMs could introduce unwanted period changes in the orbits of the two spacecraft. While these period errors are small, on the order of a second (3σ), the combined period error translates into an error in the separation rate between the two spacecraft of up to tens of kilometers per day, which is why an OTM needs to happen so soon. We chose to perform the planned OTMs using

GRAIL-A; it would be a tangential maneuver to change GRAIL-A's period to target to the desired 55 km separation at the time of the next ECM. Even so, errors in the rapid orbit determinations of the periods of GRAIL-A and GRAIL-B used in the design of the OTM and execution errors in the OTM itself will combine to introduce variation in the separation at the time of the next ECMs. This is shown by results for a monte carlo analysis for ECM-4 in figure 12. Again, this is expected to be within mission requirements and will be corrected in the design of the next ECMs, though the achieved separation following the next ECMs will be dominated by the execution errors of those maneuvers, i.e., the correction built in to the next ECMs will be lost in the noise.

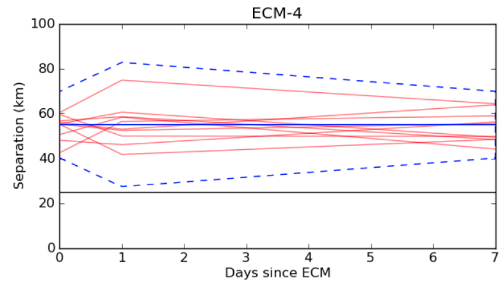

Figure 12. The three-sigma envelope of separations after ECM-4. The envelope was constructed by connecting three-sigma high and low values from the statistics at 0, 1, and 7 days generated from linear approximations of the separation for 20000 cases based on sampling a normal OD period error distribution with zero mean and 0.08 s three-sigma variance and an updated model of execution errors. A small subset of the individual cases are shown in red.

We have already discussed how one "What if?" (an overburn in ECM-1) affected the design of the TSF-XM Phase, in section II.B on page 7. We also discussed, in section II.C on page 8, how consideration of the biggest "What if?" (a missed ECM) affected the choice of the science orbit altitude and, in section II.C.2 on page 10, the eccentricity targets for each ECM. What still remains to be determined is how to recover from either of those contingency situations. In the case of a missed ECM, the maneuver can be executed at the same point in a subsequent orbit because the distance between the paths followed by the eccentricity vector stays nearly constant, but the resulting separation rate generally increases as the time after the missed maneuver grows. Alternatively, because we have designed the trajectory to be safe for at least a week after a missed maneuver, we can redesign the next ECM to compensate for the missed one. What about a missed OTM? Analysis of these contingencies and of others that may be recognized with further thought will continue throughout the LBA and TSF-XM Phases and into Science-XM Phase.

II.D. Ending the mission—an extended extended mission?

At the end of the Science-XM Phase, if all goes as planned, we will have between 15 m/s and 45 m/s of ΔV capability remaining in the propulsion system. One intriguing possibility for additional science has been identified which might justify extending the mission yet again for a few more weeks. Between Dec. 8 and Dec. 10, the spacecraft will be passing over Mare Orientale, a large impact crater on the southeastern limb of the Moon at 19° S, 93° W; it's a large crater so it takes many orbits for the entire crater to pass beneath the orbit, as shown in figure 13. The science team has expressed great interest in getting gravity data measurements from the lowest possible altitude over this feature.

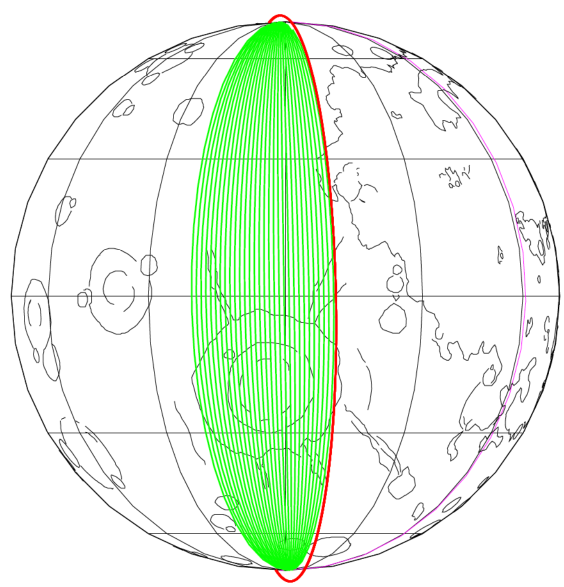

Figure 13. This Moon-fixed view shows the orbit traces above Mare Orientale during the period from Dec. 8 through Dec. 10.

Although the solar beta angle is less than 40 degrees by then, it's not too much less. The power subsystem can't support full-time orbiter-point during the orbit, but it could support the science configuration for part of an orbit, probably enough to allow measurements across the crater. Analysis of this possibility from both the science point of view and the trajectory point of view will be pursued during the coming months.

After that? Well, maybe we can do something with the inevitable impacts on the surface, following the precedent of LCROSS. This possibility will also be pursued in the coming months.

III. The completed design of the extended mission

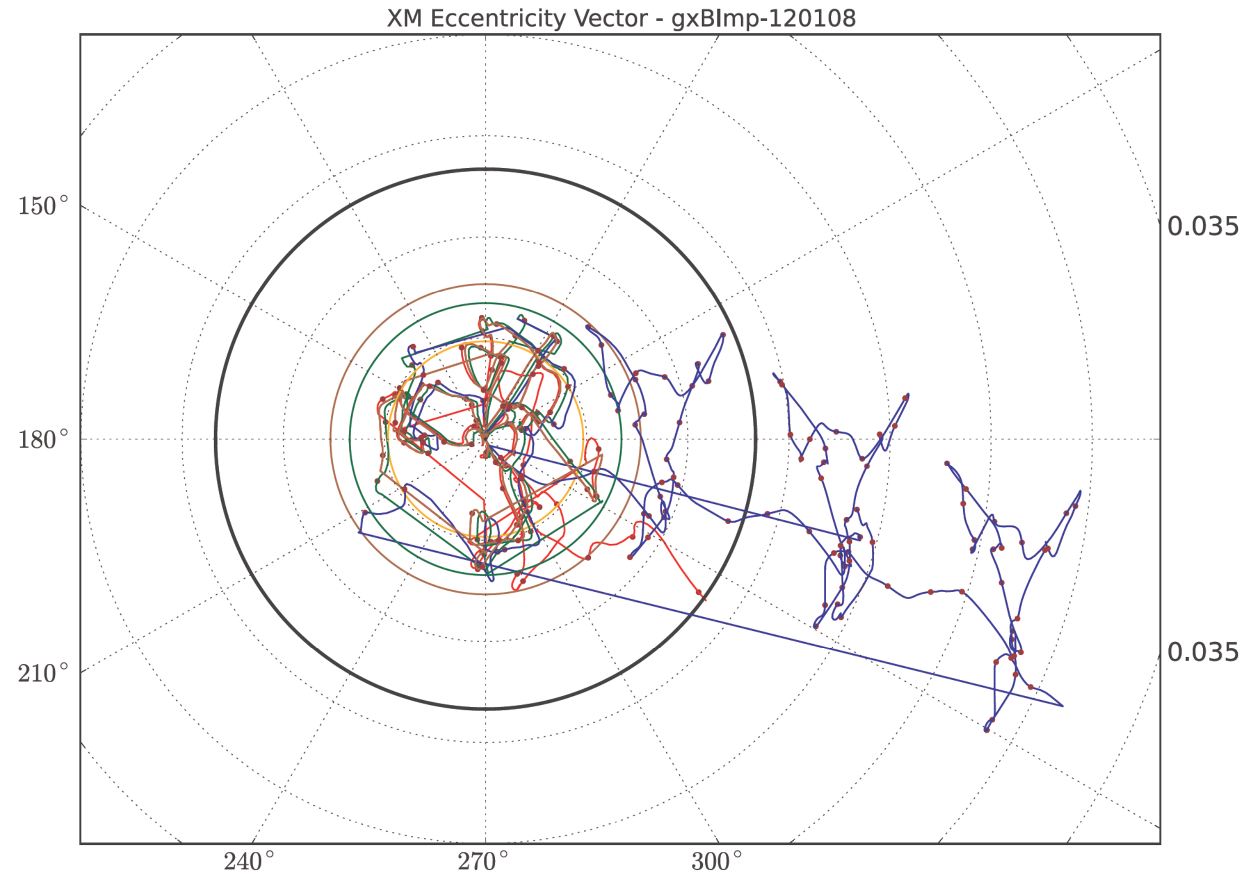

Figure 14. This polar plot, called an e-omega plot, uses eccentricity and argument of periapse as coordinates. The curve shows the evolution of the GRAIL orbit (represented by GRAIL-B's orbit) through the entire extended mission. The circles all apply to orbits with 1760.9 km semi-major axis (23.5 km altitude) with colors as follows: black at the eccentricity when the orbit touches the surface of a spherical Moon; brown for a periapse altitude of 10 km; green the minimum circle containing the eccentricity in the SCI-XM Phase; orange for a periapse altitude of 15 km.

We have presented a (mostly) time-ordered description of the design of the GRAIL extended mission. As one might have inferred in the discussions above, the actual progress of the design was not nearly so straightforward. The various phases of the mission are intricately interconnected, and decisions in the design of one phase generally affected decisions in the design of other phases. But we have a reference design in hand and indeed are in the process of flying it.

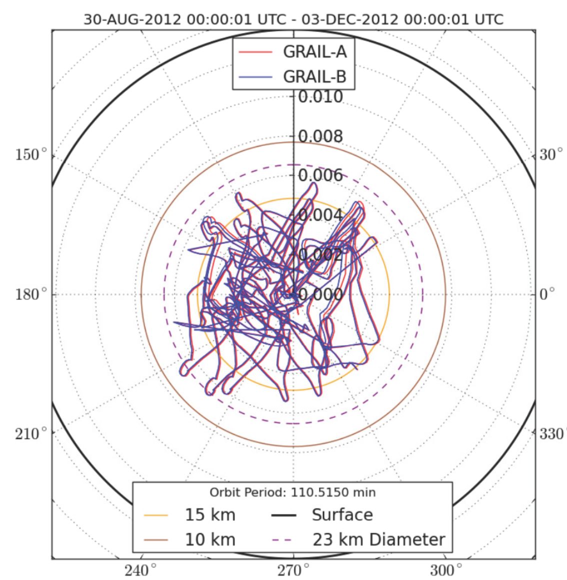

Figure 15. The paths of the eccentricity vectors for both orbiters after optimization for lifetime and ΔV during the SCI-XM Phase.

This end-to-end trajectory design is captured perhaps most completely in figures 14 and 15, which show how maneuvers affect the evolution of the eccentricity vector, although the changes in the size of the orbits are not visible here. The orbit evolution shown in figure 14 is from the trajectory design when the extended mission was proposed; it starts on 2012 May 25, a few days before the end of the science phase of the primary GRAIL mission, at a point corresponding to an eccentricity of 0.087 and an argument of periapse of 349 deg relative to the Moon's equator. As discussed by Sweetser[4] an orbit-raising maneuver not only changes the semi-major axis but it necessarily changes the eccentricity vector proportionately. The OCM which was performed to keep the spacecraft from crashing in early June shows as a straight-line shift to a point near the center of the plot. Then the long evolution during the LBA phase takes the eccentricity vector down and to the right. The ECM-1 is another tangential maneuver and shows as an even longer straight-line shift over to the left side of the eccentricity vector space, where we begin our weekly ECMs to manage the altitude for science.

The motion of the eccentricity vector during the SCI-XM Phase as originally proposed displays a pattern around the origin that repeats each mapping cycle (the cycles are shown in different colors in figure 14), which is basically one revolution of the Moon under the orbit; it is a bit surprising how little this pattern depends on the initial eccentricity vector, but it was this invariance which enabled our design process.[5] (The pattern changes more with the semi-major axis, but still displays the same basic characteristics.) After optimizing the locations of the weekly path segments to minimize the ΔV while meeting lifetime requirements, the pattern appears much more tangled. Figure 15 on the preceding page shows the eccentricity vector paths for both orbiters in the current reference orbit. As intended, the paths for GRAIL-A and GRAIL-B are virtually on top of each other. The amounts by which the segments were shifted between mapping cycles in the optimization of the paths can be seen in the displacements of the segments which stick out of the bottom of the tangle; the upper segments did not shift as much.

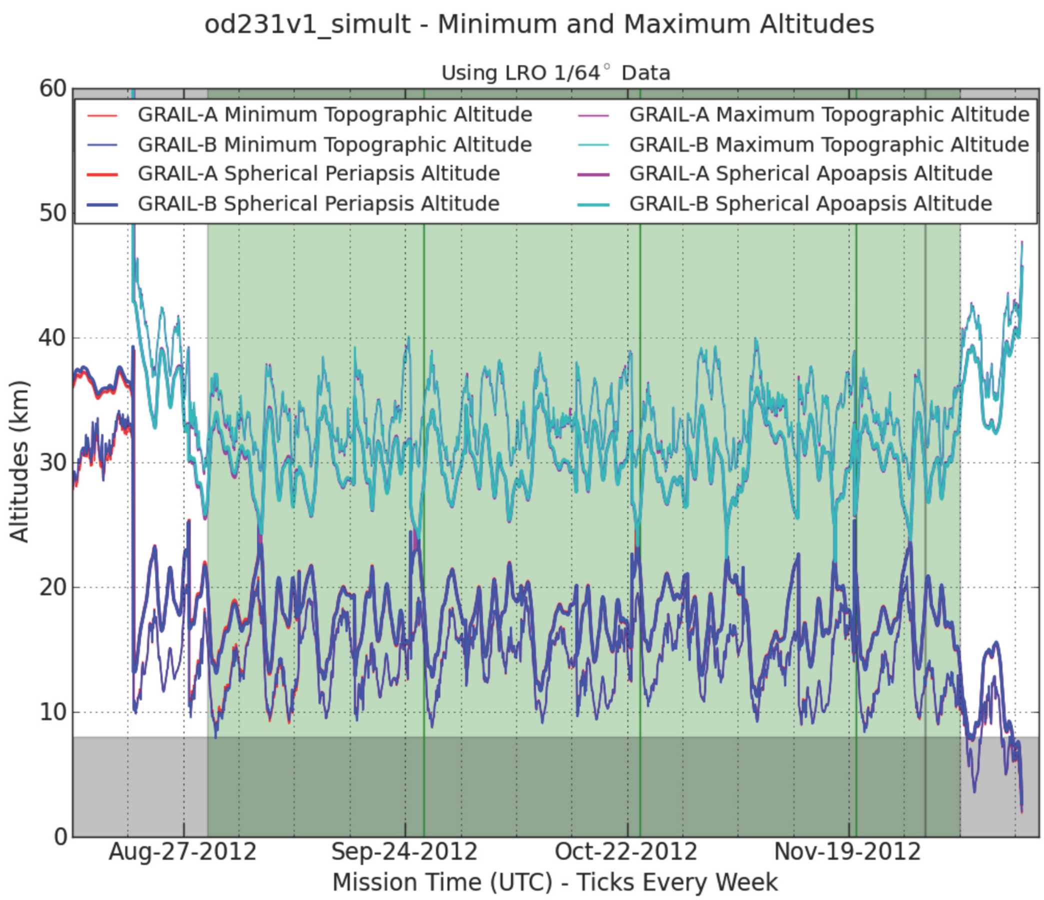

Figure 16. The spherical and topographical altitudes of both spacecraft through the TSF-XM and Science Phases. Note that they are so close for the two spacecraft that GRAIL-B's data hides almost all of GRAIL-A's data.

An alternate view, perhaps a better one, is given by the altitudes shown in figure 5 on page 6 and figure 16, which show the actual altitudes that are achieved in the current reference mission. The ΔV budget for the mission is given in figure 17 on the following page.

Mission Phase	GRAIL-XM ΔV Budget			
	Maneuver	GR-A ΔV (m/s)	GR-B ΔV (m/s)	Date (2012)
LBA	OTM-B3		0.02	20-Jun
TSF-XM	ECM-A1 / B1	38.4	37.6	20-Aug
SCI-XM	ECM-A2 / B2	10.3	10.5	27-Aug
SCI-XM	ECM-A3 / B3			03-Sep
SCI-XM	ECM-A4 / B4	9.9	9.7	10-Sep
SCI-XM	ECM-A5 / B5	9.9	9.4	17-Sep
SCI-XM	ECM-A6 / B6	10.4	10.4	24-Sep
SCI-XM	ECM-A7 / B7	7.1	7.2	01-Oct
SCI-XM	ECM-A8 / B8	7.0	7.0	08-Oct
SCI-XM	ECM-A9 / B9	8.4	8.4	15-Oct
SCI-XM	ECM-A10 / B10	10.5	10.5	22-Oct
SCI-XM	ECM-A11 / B11	6.9	7.0	29-Oct
SCI-XM	ECM-A12 / B12	9.0	9.0	05-Nov
SCI-XM	ECM-A13 / B13	9.5	9.5	12-Nov
SCI-XM	ECM-A14 / B14	10.0	10.0	19-Nov
SCI-XM	13 OTMs on GR-A	0.7		1 Day after ECMs
DCM				
GRAIL-XM ΔV Req'ts		**148.1**	**146.2**	
ΔV Capability after PM		193.3	193.3	(After OCMs)
Total ΔV Margin		**45.2**	**47.1**	Encumbered
ΔV Unc. (from prop load unc.)		30.0	30.0	Worst case
Total ΔV Margin		**15.2**	**17.1**	Unencumbered

Figure 17. The ΔV budget for the current reference mission. These numbers are not expected to change significantly through the actual mission implementation.

Acknowledgment

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